SUBSIDENCE MITIGATION IN THE SACRAMENTO-SAN JOAQUIN DELTA

Prepared for the CALFED Bay-Delta Program

by

Steven Deverel
Hydrofocus, Inc.
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Executive Summary

Subsidence on Delta islands crosses the boundaries of three of the CALFED common programs, Water Quality, Ecosystem Restoration and Levee System Integrity. Consistent with the CALFED values of integration, synergy and developing equitable solutions, subsidence mitigation needs to be addressed comprehensively. Island subsidence merits attention, future study and mitigation because of its relation to ecosystem restoration, Delta water quality, levee stability and seepage onto islands from Delta channels.

Subsidence of peat soils on Delta islands has caused the land-surface elevations to decrease since the islands were initially drained for agriculture in the late 1800's and early 1900's. The land-surface elevations of islands where peat was once present or where peat is present today range from 5 to over 20 feet below sea level. The peat soils have historically subsided at rates ranging from 0.5 to 4.5 inches per year but subsidence rates have decreased in recent years. The decreasing land-surface elevations have resulted in a decrease in the landmass resisting the hydraulic pressures on the levees and levees have been enlarged and strengthened over time. As the result of subsidence and other factors, levee failure and flooding of islands have occurred frequently since the early 1900's. A long-term approach to subsidence mitigation needs to consider a combination of non-structural and structural alternatives for managing and reversing the effects of subsidence and integrating these efforts with ecosystem restoration.

Management and reversal of the effects of subsidence in the Delta is necessary to achieve CALFED's ecosystem restoration objectives. Ecological connectivity is important for migratory fish species in the Delta, but the current lack of connectivity between Suisun Marsh west of the Delta and riparian riverine habitat east of the Delta may limit the restoration of these species. Steve Johnson of The Nature Conservancy in 1997 said: "From an ecological perspective, there needs to be tidal freshwater wetlands covering the full range of ecosystem gradients in the Delta, not just a few points here and there with the rest of the tidal wetlands hugging the shores of the eastern Delta. To achieve this range, elevations need to be restored on western Delta islands so that they can be brought back into tidal circulation." Long-term reversal of the effects of subsidence in the Delta combined with habitat restoration will be necessary to restore connectivity across the entire Delta.

Mitigation and reversal of the effects of interior-island subsidence is necessary to minimize the consequences of levee failure over the long term. Probabilistic analysis developed by the CALFED seismic hazard team suggest that levee failure is inevitable over the long-term regardless of plans to upgrade levees to PL-99 standards. The consequences and costs of levee failure and island flooding will be proportional to the depth of interior-island subsidence.

Water quality degradation in the Delta channel waters can result from levee failure in the western Delta during periods of low flow, as in the example of the flooding of Brannan and Andrus islands in 1972. This flooding required substantial operational changes in the State and Federal water projects to reestablish the hydraulic balance and compensate for salt-water intrusion. Continued subsidence on western Delta islands where there remains 10 to 60 feet of peat, will increase the volume of water that is drawn onto flooded islands thus increasing salt water intrusion and the need for dilution releases from the State and Federal water projects. For example, an average additional foot of subsidence on Sherman Island (at the rate of 0.5 inch per year this will occur in 24 years) would create about 9,900 acre feet of additional volume below sea level. This additional volume of water could be drawn from the west during flooding and could increase reclamation costs. Repairs and upgrades of Delta levees can cost from several tens of thousands of dollars to over 1 million dollars per mile.

Seepage onto Delta islands will increase as the difference in the water level in the channel and the groundwater level on the islands increases due to continued subsidence and deepening of drainage ditches. Increased seepage may require increased volumes of drainage to be pumped from Delta islands and increased pumping capacity and pumping costs. Increased drainage volumes may lead to increased loading of dissolved organic carbon to Delta channels. Increased seepage may also detrimentally affect levee stability.

The objectives of this report are to summarize the current knowledge of the causes, rates and effects of subsidence, to present the information about non-structural alternatives for stopping and reversing the effects of subsidence and to recommend directions for future research and data collection. The approach was to 1) review and summarize the available literature, 2) determine the relative magnitude of the different causes of subsidence using the available data, 3) use the areal distribution of historic subsidence rates and peat thickness to delineate priority areas for subsidence mitigation and future study and 4) determine and describe possible mitigation measures and future data collection efforts.

Consistent with the May, 1997 Governor's Flood Emergency Action Team Report that recommended that "proactive nonstructural floodplain management strategies...be implemented to reduce future flood loss and curtail the spiraling cost of State and Federal disaster assistance", this report describes non-structural options for subsidence mitigation. This report is a first step towards implementation of subsidence mitigation measures on Delta islands. The focus is the subsidence of peat soils on Delta islands. Levee subsidence that occurs primarily as the result of consolidation of organic materials underlying levees is described in another report that focuses on levee integrity.

The results of the analyses presented here indicate that present-day subsidence in the Sacramento-San Joaquin Delta is primarily the result of microbial oxidation of the peat soils. The peat soils contain a complex mass of carbon that microbes such as bacteria and fungi use as an energy source thus oxidizing the carbon to carbon dioxide gas. The available data indicate that historically, microbial oxidation caused 29 to 55 percent, consolidation and shrinkage caused 22 to 29 percent, wind erosion caused 3 to 34 percent and burning caused 9 to 24 percent of the total subsidence that occurred from the late

1800's through the 1970's. Consolidation continues to occur as the elevations of drainage ditches are lowered in response to subsidence due to microbial oxidation. Burning and wind erosion no longer appear to be significant causes of subsidence.

This report summarizes the data for changing land- and water-management practices for stopping and reversing the effects of subsidence of the peat soils. The results of research conducted by the USGS in cooperation with DWR on Twitchell Island indicate that seasonal wetlands in which the land is flooded during the fall and winter and drained in the spring and summer will not stop subsidence or reverse its effects. The primary cause of subsidence is carbon loss due to microbial oxidation of the peat. This oxidation is highest during the spring and summer. In general, land- and water management practices that result in drained and oxidized conditions during the spring and summer will result in a net carbon loss and continued subsidence. In contrast, permanent shallow flooding to a depth of about one foot resulted in a net accumulation of carbon which lead to the accumulation of biomass. The results of coring in the experimental flooded pond showed that about 3 to 6 inches of firm biomass accreted from 1993 to 1997 during 2 years of growth under full vegetative cover and 2 years of growth under partial vegetative cover. Capping of the peat with mineral material in the laboratory reduced carbon loss from the peat.

A Geographic Information System developed and housed at the Department of Water Resources Central District and available data for subsidence rates and peat thickness were used to delineate priority areas for subsidence mitigation. Figure 2 shows the location of the priority areas. There are about 23,000 acres in first priority area that includes lands where time-averaged subsidence rates from the early 1900's to the mid-1970's were 1.5 inch per year or greater and the peat is greater than 10 feet thick. There are about 36,000 acres in the priority 2 area that includes lands where time-averaged subsidence rates were greater than 1.5 inch per year and the peat is equal to or less than 10 feet thick. Lands in the priority 1 area are generally located in the central and central-western Delta where there is relatively deep peat and time-averaged subsidence rates have been generally high. Large tracts of land in the western Delta are also included in the priority 1 area. Most of the lands in the priority 2 area are in the central and central-eastern Delta where there have historically been high rates of subsidence but the peat thickness is generally less than 10 feet.

The error in the determination of areas in each priority varies depending on the magnitude of the time-averaged subsidence rate and the error in the peat thickness data. Where time-averaged subsidence rates were generally greater than 1.5 to 2 inches per year, the possible error in the delineation of the priority areas appears to be low. Where time-averaged subsidence rates are less than or equal to 1.5 inch per year, the error can be large. The peat thickness estimates can be in error due to lack of data for specific areas and because the data are based on land surface elevation data that are over 20 years old. The possible error in the delineation of priority areas for subsidence mitigation and slowing of subsidence rates in recent years points to the need for data collection to determine the present-day magnitude and areal distribution of subsidence rates.

The delineation of priority areas for subsidence mitigation is a first step towards implementation, designed to identify areas where future research and data collection efforts are needed. There is still much to be learned about subsidence, subsidence mitigation and the effects of subsidence. A comprehensive CALFED program is needed to effectively conduct and integrate future subsidence mitigation efforts. Additional data collection and research are required to:

- quantify and predict present-day and future subsidence rates,
- determine the present-day areal distribution of peat thickness,
- refine the delineation of priority areas for subsidence mitigation,
- temporally and spatially define the effects of subsidence on levee stability,
- determine the influence of future subsidence on levee foundation deformation and seepage through levees,
- determine the effects of continuing subsidence on future land use,
- determine the effects of future land subsidence on drainage water quality in Delta channels and seepage onto islands,
- develop land- and water-management practices for stopping and reversing the effects of subsidence and
- integrate subsidence mitigation into ecosystem restoration efforts.

This report resulted from a cooperative effort among the Department of Water Resources Central District (DWR), U.S. Geological Survey (USGS), the CALFED Bay-Delta Program and HydroFocus, Inc. DWR funded the majority of the data analysis and data collection described in this report related to the causes of subsidence, delineation of priority areas for subsidence mitigation and development of options for stopping and reversing the effects of subsidence. USGS provided partial funding for data collection and analysis related to the development of options for stopping and reversing the effects of subsidence and provided comments on this report. CALFED provided the majority of the funds for the writing of this report. Hydrofocus, Inc. donated time and materials for the writing of this report. The Natural Heritage Institute also provided comments on the report.

SUBSIDENCE MITIGATION IN THE SACRAMENTO-SAN JOAQUIN DELTA

1.0 Introduction and Background

Prior to 1850, the Sacramento-San Joaquin Delta was a tidal wetland. The Delta was drained for agriculture in the late 1800's and early 1900's (Thompson, 1957). The organic or peat deposits of the Delta formed during the past 7,000 to 11,000 years from decaying plants at the confluence of the Sacramento and San Joaquin Rivers (Atwater, 1982 and Schlemon and Begg, 1975). The drained peat soils on over 60 islands and tracts are highly valued for their agricultural productivity and have undergone continuous subsidence since they were initially drained[1]. A network of levees protects the island surfaces that range from 5 to over 20 feet below sea level, from inundation.

Drainage of the Delta islands was essentially complete by the 1930's when the Delta assumed its present configuration of the islands and tracts surrounded by 1,100 miles of man-made levees and 675 miles of channels and sloughs. When most of the original levees were constructed on foundations of sand, peat and organic sediments, the difference between the water level in the channels and island surfaces was less than 5 feet. Because of the decreasing island-surface elevations due to subsidence, there has been a decrease in the landmass resisting the hydraulic pressures on the levees and the levees have been enlarged and strengthened over time.

As the result of subsidence and other factors, levee failure and flooding of islands has occurred since the early 1900's. Prokopovitch (1985) reviewed the history, causes and costs of flooding of Delta islands since the early 1900's and the information in this and the following paragraph was excerpted from pages 409-410 of his journal article. Island flooding in the early 1900's resulted mainly from overtopping of levees during high tides or spring and winter flooding. With the flood control provided by the construction of the Central Valley Project in the 1940's, overtopping became less of a factor and levee foundation instability increasingly became an important factor in island flooding. Over 50 islands or tracts have flooded since 1930.

The data for cost of levee failures and flood damage are incomplete. However, as an example, the cost associated with 11 of the 28 islands that flooded from 1969 to 1983 was about $177 million. Levee failure and island flooding can result in loss of agricultural, commercial, industrial and residential property, recreational use, communication lines and storage and transport of electricity and natural gas. The cost for levee maintenance, upgrades and repair generally ranges from several tens of thousands to over 1 million dollars per mile. Subsidence contributes to the need for levee upgrades

[1] Subsidence is defined here as the decrease of land surface elevation. Subsidence in this report refers to the decrease in land surface elevation on the areas of the islands and tracts on the land side of the levees and is different from the lowering of the levee surface as the result of compaction of foundation materials.

and maintenance. Subsidence mitigation needs to be an integral part of any plan to prevent future flooding of Delta islands.

The cited causes of land subsidence in the Delta include aerobic microbial oxidation of soil organic carbon or microbial oxidation, anaerobic decomposition, consolidation, shrinkage, wind erosion, gas, water and oil withdrawal and dissolution of soil organic matter (Prokopovitch, 1985, Department of Water Resources, 1980; Weir, 1950). Stephens and others (1984) identified 6 causes of subsidence in drained organic soils worldwide; shrinkage due to desiccation, consolidation, compaction as the result of tillage, wind and water erosion, burning and microbial oxidation. Stephens and others (1984) reported that 53 percent of historical subsidence in organic soils in the Florida Everglades was due to microbial oxidation. Schothorst (1977) computed the percentage of the different causes of subsidence in organic soils in the Netherlands to be compaction, 28 percent; shrinkage, 20 percent; and microbial oxidation, 52 percent. The relative percentage of the different causes of subsidence in Delta have heretofore have not been quantified.

1.1 Purpose, Scope and Approach

To effectively mitigate the effects of subsidence in the Delta, the effects, rates and causes of subsidence and methods for stopping or reversing the effects of subsidence need to be identified and quantified. This report 1) summarizes information about the effects, causes and rates of subsidence, and 2) presents information about and recommendations for subsidence mitigation and future data collection.

The approach was to 1) review, synthesize and summarize the available literature and available research results, 2) estimate the relative magnitude of the different causes of subsidence using the available data, 3) use the areal distribution of historic subsidence rates and peat thickness to delineate priority areas for subsidence mitigation and future study and 4) determine and describe mitigation measures and future data collection efforts.

The overall approach for estimating the relative magnitude of the causes of subsidence was to use a computer model to synthesize and integrate the available data for subsidence rates and causes. The model estimated the amount of yearly subsidence due to different causes based on available data. The model results were compared with measured elevation change for five islands; Jersey, Sherman, Bacon and Mildred Islands and Lower Jones Tract.

The approach for the delineation of priority areas for subsidence mitigation was to use a geographic information system (GIS) developed by the Department of Water Resources Central District to analyze available data for the Delta for subsidence rates, depth of peat soils and soil characteristics. The Department of Water Resources (1980) mapped the islands of greatest subsidence and listed the peat thickness for each island. The representation of the areal distribution of subsidence rates and peat thickness presented here is an improvement relative to the previous effort (Department of Water Resources,

1980) because 1) the error in the estimated subsidence rate is generally lower, quantifiable and the result of temporally uniform elevation change determinations, and 2) the estimates for peat thickness are based on more recent and comprehensive data. Also, the data was entered into a GIS which facilitated the evaluation of the data for delineation of priority areas in greater areal detail than entire islands such as generally presented in Department of Water Resources (1980).

2.0 Methodology

2.1 Methodology for Estimating the Relative Magnitudes of the Causes of Subsidence

A computer model was developed to estimate yearly subsidence. The simulated causes of subsidence were aerobic microbial oxidation of organic carbon, consolidation and shrinkage, wind erosion, burning and withdrawal of natural gas and groundwater. Subsidence due to aqueous carbon loss was not simulated because data presented by Deverel and Rojstaczer (1996) indicated that it accounts for less than 1 percent of the measured subsidence. Data presented in Deverel and others (1998) indicated that anaerobic decomposition of Delta organic soils is small relative to other causes of subsidence and was also not included in the model. The data and methodology for simulating the causes of subsidence are summarized here and are described in detail in Appendix A.

2.1.1 Microbial Oxidation

The carbon flux data for Jersey Island collected from 1990 to 1992 (Deverel and Rojstaczer, 1996) was used to approximate the relation of microbial oxidation of organic carbon to soil organic carbon content. This relation was then used to simulate subsidence due to microbial oxidation for Jersey Island at the study location of Deverel and Rojstaczer (1996). The mass of carbon lost by microbial oxidation was assumed to follow Michaelis-Menton kinetics (Conn and Stumpf, 1976). In the Michaelis-Menton equation, the amount of carbon loss due to microbial oxidation is proportional to the amount of organic carbon in the soil.

2.1.2 Consolidation and Shrinkage

When the organic soils of the Delta were initially drained, there was substantial consolidation and shrinkage due to water loss. There is also annual consolidation that is a result of an effective stress on the peat material near the water table. As the soil subsides and oxidizes, the elevation of the bottom of drainage ditches is decreased to lower the water table thus decreasing the buoyant force of water supporting the peat. There is also an increase in loading due to the increasing density of the oxidizing soil. Shrinkage may also cause a loss in volume as the peat soils are dried but this has not been well quantified in the Delta. This annual subsidence due to consolidation was simulated in the model as equal to the volume of water lost when the water table is lowered. The amount of initial shrinkage and consolidation during reclamation was estimated from an empirical equation presented in Eggelsmann and others (1990).

2.1.3 Wind Erosion

Wind erosion of peat soils caused dust storms that affected Stockton, Lodi and Tracy prior to the early 1960's (Alan Carlton, former University of California Extension Specialist for the Delta, personal communication, 1997). The prevailing westerly winds of oceanic air masses moving to the Central Valley caused dust storms primarily during May and June (Schultz and Carlton, 1959; Schultz and others, 1963). There are few reported values of annual amounts of peat soil eroded by wind that range from 0.1 to 0.57 inch per year (Department of Water Resources, 1980; Carlton, 1965).

Crop histories in Thompson (1958) and the Weir transect notes (see Rojstaczer and others, 1991) were used to determined the spatial distribution of crops grown on the islands where land surface elevation changes were simulated. Wind erosion was calculated at varying rates of 0.1 to 0.57 inch per year where asparagus was grown or where the land was fallow. There was generally a shift from the planting of asparagus and other vegetable crops to corn in the Delta in the 1950's and 1960's and the model calculated minimal wind erosion after 1965.

2.1.4 Burning

Weir (1950) and Cosby (1941) estimated that the peat soils were burned once every 5 to 10 years. Data analysis in Rojstaczer and Deverel (1995) and Rojstaczer and others (1991) indicated that burning occurred more frequently during World War II when potatoes were grown extensively. Burning was used to control weeds and diseases and to create ash for potatoes. Weir (1950) stated that 3 to 5 inches of peat were typically lost during a single burning. Burning was simulated differently for the islands depending on the distribution of crops following the information presented in Cosby (1941) and Weir (1950).

2.1.5 Withdrawal of Natural Gas

Since the discovery of the Rio Vista Gas field in the 1930's, several natural gas fields have been developed in the Delta. Compaction of the sediments could occur if the gas reservoirs were substantially depressurized which could result in subsidence of Delta islands. To determine the subsidence due to natural gas withdrawal, sediment cores collected from channel islands were dated by determining the levels of cesium-137 at 1-inch depth intervals (Rojstaczer and others, 1991). Records from the California Department of Conservation, Division of Oil and Gas, indicate that gas production began to increase substantially in the mid-1950's and gas withdrawal was simulated as a contributor to subsidence in the model after 1955.

2.1.6 Simulation of Total Subsidence

The total annual depth of subsidence was estimated by summing the depths of subsidence due to the different causes for each yearly time step. The model accreted the land surface as it progressed backward in time based on the mathematical representation of the causes of subsidence. The soil organic carbon content and bulk density were estimated for the most recent elevation data and were recalculated for each subsequent time step. Subsidence and the microbial oxidation of organic carbon were simulated as a two-layer process based on data presented by Carlton (1966). The soil organic matter content was recalculated for each layer at each time step based on the simulated change in the total mass of carbon for each layer.

2.2 Methodology for Delineation of Priority Areas for Subsidence Mitigation

The delineation of priority areas for subsidence mitigation in the Delta is based on the areal distribution of historical, time-averaged subsidence rates calculated from the early 1900's to the mid-1970's and peat thickness. The first priority area was chosen to include those lands where the time-averaged subsidence rates were high (greater than 1.5 inch per year) and where there is still substantial peat (greater than 10 feet) remaining. The second priority area was chosen to include those areas where the time-averaged subsidence rates were high (greater than 1.5 inch per year) but there was 10 feet or less of peat remaining. It was assumed that the distribution of time-averaged subsidence rates generally reflects the relative distribution of present-day subsidence rates. Areas where time-averaged subsidence rates were lower than 1.5 inch per year were not considered to be high priority areas for immediate subsidence mitigation. A Geographic Information System for the Delta developed by, and housed at the Department of Water Resources Central District was used for the delineation of priority areas. The methodology used is summarized here and described in detail in Appendix B.

Two sets of US Geological Survey topographic maps were used to estimate the time-averaged rates of subsidence throughout the Delta from the early 1900's to 1974 through 1978. The difference in elevation between the two time periods was estimated to be the total depth of subsidence. The time-averaged rate of subsidence was calculated as the total amount of subsidence divided by the time interval that ranged from 60 to 72 years. The error in the subsidence rate estimate results from the error in the elevation estimate from the topographic maps and the change in mean sea level datum from the early 1900's to 1976 to 1978. The methodology for estimating the error associated with the time-averaged subsidence rate is described in Appendix B.

The peat thickness was calculated as the difference between the basal elevation of peat and peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps. Atwater's (1982) peat and peaty mud of tidal wetlands include the organic deposits derived from decayed vegetation that formed during the sea level rise during the last 7,000 years. Atwater's (1982) delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soil surveys.

The peat thickness data was compared with the delineation of organic soils or highly organic mineral soils in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993). Where there were discrepancies between the two sources of information for the extent of peat soils, the soil survey data was assumed to be correct.

The delineation of soil series as mapped in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993) were entered in digital form into the GIS developed by the Department of Water Resources Central District. The soil organic matter content was the primary soil characteristic of interest. The soil organic matter content was estimated for the 11 soil series which were either organic soils or highly organic mineral soils based on the data provided in the soil surveys.

3.0 Effects of Subsidence

Levee stability is directly affected by continued subsidence within a zone of influence adjacent to levees. The spatial and temporal definitions of the zone of influence have not been quantified for the Delta and are site specific. The temporal and spatial definitions of the zone of influence should be based on analysis of the effects of future subsidence primarily on seepage and deformation of levee foundations. Deformation analysis (e.g. Foote and Sisson, 1992) of Delta levees heretofore have not considered the effects of future subsidence.

Seepage onto Delta islands will increase due to future subsidence. As the water level on the island is lowered as the result in increased drainage depth, the hydraulic gradient from the water surface in the channel to the groundwater in the interior of the island will increase. This will in turn increase the rate of seepage onto the island and may affect seepage through the levee and the erosion of foundation materials. Future data collection and analysis are needed to determine these effects.

Seepage onto Delta islands is removed, along with agricultural return flows, through a network of drainage ditches and one or more drainage pumps that pump drainage water from the islands into the channels. Templin and Cherry (1997) quantified the volume of drainage water pumped from Delta islands in 1995. Their data indicate that volumes of drainage water ranged from 2 to 4 acre-feet per acre in the central and western Delta. As a point of reference, average reference evapotranspiration for the Delta (Orang and others, 1995) is about 4.5 feet. Actual consumptive use of water by crops is less than reference evapotranspiration. About 260 agricultural drains discharge and contribute to high dissolved organic carbon (DOC) loading into the Delta channels as the result of leaching of the organic soils (Department of Water Resources Municipal Water Quality Investigations Program, 1997). High DOC concentrations can result in unacceptably high concentrations of disinfection byproducts when the water is treated for drinking. Because of increasing seepage volumes, drainage loads for DOC and disinfection byproducts may increase with increasing subsidence.

Unintentional flooding of Delta islands as the result of levee failures can cause additional water quality degradation due to salinity intrusion. Past subsidence has resulted in reduced landmass to support levees and continued subsidence can exacerbate the water quality effects of flooding by increasing the volume of water that will move onto the island during flooding. Cook and Coleman (1973) described the effects of flooding of Andrus and Brannan islands in June 1972. The Brannan-Andrus flooding is the only documented example of water quality degradation as the result of island flooding. The water balance in the Delta was upset as the result of the levee failure as 150,000 acre-feet of water moved onto the islands that in turn resulted in the movement of salt water from the west into the Delta. State and Federal exports of water from the Delta were temporarily reduced and releases from Central Valley Project reservoirs were increased to reduce the salinity intrusion. The total cost of the flooding was $22.5 million. Three hundred thousand acre-feet of additional water were released from storage from State and Federal water projects.

Short-term water quality problems probably would not occur if breaks occur during winter periods of high flow. Nor do water quality problems occur with all flooding during periods of low flow. The extent of water quality degradation is dependent on the location of the flooding and the flow conditions. Island flooding in the western Delta during low flow periods is the primary concern. Several of the western Delta islands have depths of 10 to 60 feet of peat remaining and continued subsidence will increase the volume of water that will move onto the island during flooding. For example, on Sherman Island an additional foot of subsidence over the entire island during the next 24 years (0.5 inch per year) will result in an additional volume of 9,900 acre-feet below sea level that can move onto the island during flooding. Probabilistic analysis developed by the CALFED seismic hazard team suggest that levee failure is inevitable over the long-term regardless of plans to upgrade levees to PL-99 standards. The consequences and costs of levee failure and island flooding will be proportional to the depth of interior-island subsidence.

4.0 Rates and Causes of Subsidence

4.1 Rates of Subsidence

Cited historic and time-averaged rates of subsidence in the Delta range from about 0.5 to 4.6 inches per year (Rojstazcer and others, 1991; Prokopovich, 1985, Department of Water Resources, 1980). Department of Water Resources (1980, p. 1) stated that estimates of subsidence for the years 1911 to 1952 were 3.0 inches per year on 17 Delta Islands or tracts. Department of Water Resources (1980) also listed the total amount of subsidence for 21 islands as ranging from 10 to 21 feet and time-averaged rates ranging from 1 to 4.6 inches per year. Prokopovitch (1985, p. 405) reported the same range for time-averaged subsidence rates. Rojstaczer and others (1991) evaluated subsidence from changes in land-surface elevations against power pole foundations installed in 1910 and 1952 in 1987 on Sherman and Jersey Islands. The time-averaged subsidence rate from 1910 to 1987 ranged from 0.5 to 1.2 inch per year. The time-averaged subsidence rate from 1952 to 1987 ranged from less than 0.3 to 0.7 inch per year. This and information presented by Rojstaczer and Deverel (1993) indicate that subsidence rates have slowed in recent years.

Rojstaczer and Deverel (1993) determined that a logarithmic expression for the decrease in the land-surface elevation over time statistically fit the data best for Bacon and Midlred islands and Lower Jones Tract where the time averaged historic subsidence rates were 2 and 3 inches per year from 1924 to 1981. The estimates for subsidence rates in 1980 for these three islands ranged from 1.2 to 1.6 inch per year (Rojstaczer and Deverel, 1993). Subsidence rates are slowing for two reasons. First, the rate of microbial oxidation is proportional to the amount of organic carbon in the soil which is decreasing with time. Second, other factors such as wind erosion and burning contributed to subsidence in the past but do not appear to contribute significantly to present-day subsidence. Deverel and Rojstaczer (1996) continuously measured present-day subsidence rates from 1990 to 1992 by on Sherman and Jersey Islands and Orwood Tract. These authors reported rates of 0.2, 0.24 and 0.32 inch per year on Sherman, Jersey and Orwood, respectively.

4.2 Causes of Subsidence

4.2.1 Simulation Results

Table 1 shows the range of simulated elevation changes and percentages of the total subsidence due to the different causes. The results in Table 1 for the different simulations reflect variations in the amount of wind erosion for all the islands and the parameters in the Michaelis-Menton equation for microbial oxidation.

Table 1. Simulated changes in elevation and causes of subsidence for Jersey, Sherman, Mildred and Bacon islands and Lower Jones Tract.

			Simulated range in percent of total subsidence due to:				
Island (years of simulation)	Simulated changes in elevation (in feet)	Measured change in elevation (in feet)	Microbial oxidation	Consolidation and shrinkage	Wind erosion	Burning	Gas with-drawal
Jersey (1886 –1975)	5.3 – 8.1	6.7 +/- 2.5	31 – 48	22 – 25	11 –26	9 – 13	2 – 3
Sherman (1910 – 1987)	4.7 – 6.05	6.0 +/- 1.0	29– 47	24 – 25	9 – 34	10 – 14	
Mildred (1924 – 1981)	10.8 – 11.4	11.6 +/- 2.0	37 – 50	29 – 30	3 – 17	18 –19	
Bacon (1924 – 1978)	10.5 – 11.0	10.5 +/- 1.0	36 – 49	24 – 25	3 – 17	23 – 24	
Lower Jones (1924 – 1981)	10.0 – 10.4	9.45 +/- 1.5	41 - 55	24 – 25	3 – 18	18 - 19	
Total range	-	-	29 – 55	22 – 29	3 – 34	10 - 24	2 - 3

The most recent elevation data for Jersey Island in Table 1 is from the 1978 topographic map that shows topography from photogrammetric methods using aerial photos conducted in 1974 and plane table elevation data collected in 1976. Thompson (1957) indicated that Jersey Island was initially drained in 1886. The measured elevations for Sherman Island in Table 1 were from elevations determined in 1988 against power pole foundations installed in 1910 (Rojstaczer and others, 1991; Rojstaczer and Deverel, 1995). The estimated error for the Sherman data was about 1 foot (Rojstaczer and others, 1991). The estimated error in the Jersey elevation change is about 2.5 feet. The measured changes for Mildred, Bacon and Lower Jones were from the leveling data collected along the Weir transect (Weir, 1950) by University of California personnel (see Rojsatczer and others, 1991).

Table 1 shows that the primary causes of historical subsidence simulated on the five islands are microbial oxidation of organic carbon (29 to 55 %) and consolidation and shrinkage (22 to 29 %). Much of the consolidation for Jersey and Mildred islands occurred when these islands were initially drained. This accounts for the relatively large percentage of total simulated subsidence due to consolidation for these islands. The Jersey Island simulation extends from the approximate year of initial drainage to 1975 when the most recent elevation data was collected. The Mildred Island simulation extended from 1924 (the year of initial drainage) through 1981 to coincide with the leveling data reported in Rojstaczer and others (1991).

The amounts of the different causes of subsidence varied with time. Figure 1 shows the amount of subsidence contributed by the different processes for the five islands from 1886 to 1985 in 10-year intervals. Consolidation is the predominant process during the first year after initial drainage. Burning was the predominant cause in 1945. Wind erosion and gas withdrawal are minor causes that account for less than 10 percent of the total yearly subsidence. Simulation results for 1975 on Jersey, Mildred, Bacon and Lower Jones and 1985 on Sherman indicate that present-day subsidence is caused primarily by microbial oxidation and consolidation (75 percent and 25 percent, respectively). Deverel and Rojstaczer (1996) also studied present-day subsidence from 1990 to 1992 on Jersey and Sherman Islands and Orwood Tract. Their results indicated that 60 to 76 % of the measured subsidence was due to microbial oxidation. Comparison of model results and measured elevations shown in Apendix A indicate good agreement between simulated and measured results for Mildred, Bacon and Lower Jones.